2-µm Brillouin laser based on infrared nonlinear glass fibers

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Infrared fiber materials such as chalcogenide, tellurite and heavily Germania-doped silica glasses are attractive materials for many applications based on nonlinear optical effects such as Kerr, Raman and Brillouin processes. Here, we experimentally demonstrate a close-to-single-frequency Brillouin fiber laser in the 2-µm wavelength region either based on tellurite (TeO_2) glass or on heavily Germania-doped silica glass. Our results reveal a strong enhancement of the Brillouin gain efficiency at 2-µm more than 50 times that of standard silica optical fibers. A lasing threshold and narrow linewidth of 98 mW and 48 kHz have been demonstrated in the tellurite fiber-based laser. This simple Brillouin laser source configuration confirms the potential applications of such fibers for the development of nonlinear photonic devices in the important 2-µm spectral range.

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1. INTRODUCTION

Stimulated Brillouin scattering (SBS) in optical fibers is a key nonlinear optical effect with important applications such as distributed optical fiber sensing, microwave photonics, Brillouin spectroscopy, and optical storage and fiber lasers [1–5]. The latter application has attracted significant interest as highly coherent laser sources with sub-Hz laser linewidth have recently been achieved using SBS in simple all-fiber passive optical cavity and in high-Q resonators [6–8]. To date, most of Brillouin lasers have been designed to operate at telecom wavelengths (~ 1.55 µm) based on several materials such as a silica-on-silicon disk resonator [9], highly nonlinear fibers (HNLF) [10], tellurite-based optical fibers [11], and chalcogenide glass photonic chips and fibers [12,13]. However, for a range of mid-infrared applications like high resolution molecular sensing and coherent LIDAR, there is a need to develop narrow-linewidth laser sources at longer wavelengths. Recently, only a few studies on Brillouin fiber lasers (BFLs) have been reported in the 2-µm spectral range [14–16]. For instance, Luo et al. demonstrated in 2014 a single-frequency BFL operating at 2-µm, in which three strong pump diodes with a total power of 18 W were employed to overcome a high lasing threshold of 1.04 W [14]. The lasing threshold was later lowered to 52 mW using a chalcogenide ($As_{38}Se_{62}$) glass suspended-core optical fiber as the Brillouin gain medium [15]. In another study, a widely tunable Brillouin laser based on a thulium-doped fiber laser pump and a segment of highly Germania-doped optical fiber (75-mol % GeO_2 doping level) has been demonstrated with a low threshold of 47 mW only [16].

Tellurite (TeO_2) -glasses ~~optical fibers~~ also appear as very attractive material for Brillouin scattering around 2 µm. In addition to providing high Brillouin gain efficiency and narrow linewidth, they also exhibit low loss at 2 µm compared to silica glass [14]. To the best of our knowledge, no 2-µm BFLs based on a tellurite optical fiber or heavily GeO_2-doped-core optical fibers with 98-mol% doping level have been reported yet.

In this paper, we demonstrate a low-threshold single-frequency BFL at 2-µm ~~either~~ based on step-index tellurite (TeO_2) optical fiber. Our results reveal very good performances at 2 µm compared to previous works. More specifically, a lasing threshold and narrow linewidth of 98 mW and 48 kHz have been demonstrated, thus confirming the strong potential of soft-glass fiber~~-based lasers~~ s ~~in~~ for ~~the~~ Brillouin applications.~~mid-infrared.~~ We further investigated the potential of a heavily GeO_2-doped-core optical fibers with 98-mol% doping level for Brillouin lasing at 2 µm and we show a higher power threshold up to 645 mW.

The paper is organized as follows: we first investigate SBS in a short segment of each fiber to get the Brillouin frequency shift and threshold, a Brillouin laser cavity is then experimentally investigated by using a passive fiber ring cavity configuration incorporating the TeO_2-based optical fiber. Finally, we compare and discuss the performances of the BFLs developed at 2 µm with another heavily GeO_2-doped-core optical fiber and with previous works using a chalcogenide-glass ($As_{38}Se_{64}$) optical fiber and an SMF-28.

2. EXPERIMENTAL SETUP

Figure 1 shows a simple configuration of the BFL similar to that described in Ref. [13]. A tunable narrow-linewidth continuous-wave diode laser around 2 µm (Thorlabs TLK-L1950R) was used as a pump laser. The pump wave was amplified up to 29.5 dBm using a thulium doped fiber amplifier (TDFA) and injected into the nonlinear fiber under test (FUT) by use of an optical circulator (OC). An additional short segment of ultrahigh numerical aperture (UHNA) fiber was used for butt-coupling into TeO_2 glass-based fibers. A 99:1 fiber tap coupler was inserted to extract and characterize the BFL signal while the remaining 99% of the Stokes wave was fed back into the passive fiber ring cavity. The Brillouin Stokes waves, in this configuration, perform multiple round-trips, while the pump laser travels in the backward direction is isolated by the circulator. A polarization controller was also inserted into the cavity to ensure that the polarization of the Stokes wave is kept parallel to that of the pump laser to maximize the Brillouin gain. The output BFL light is then sent into an optical spectrum analyzer (OSA, Yokogawa AQ6375) with a resolution of 10 GHz and a high-speed 2 µm photodiode (PD, Newport, 818-BB-51AF) for optical and radio-frequency (RF) spectrum measurements.

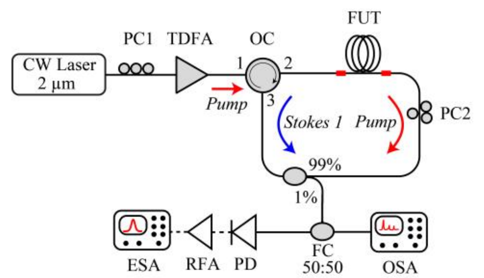

Fig. 1. Experimental setup of Brillouin fiber laser cavity. CW: Continuous wave, TDFA: Thulium-doped fiber amplifier, PC: Polarization controller, OC: Optical circulator, FC: Fiber coupler, FUT: Fiber under test, OSA: Optical spectrum analyzer, RFA: Radio-frequency amplifier, ESA: Electrical spectrum analyzer, PD: Photodiode.

The fiber cavity consisted of a 2-m-long segment of tellurite step-index fiber whose core and cladding compositions are $80TeO_2$-$5ZnO$-$10Na_2O$-$5ZnF_2$ (TZNF, molar fraction) and $60TeO_2$-$5ZnO$–$20Na_2O$-$15GeO_2$ (TZNG), respectively. Another 1.8-m-long segment of heavily GeO_2-doped-core optical fibers with 98-mol% doping level was used for a further comparison. The optical circulator, polarization controller, and fiber coupler are all made of standard single-mode silica fiber (SMF1950) with a total length of 3 m that belongs to the cavity (i.e., the total cavity length is equal to 5 or 4.8 m, respectively). The corresponding free spectral range (FSR) of both cavities under study is estimated in the ~40 MHz range, close to the Brillouin gain linewidth, so that the number of the longitudinal modes that can be amplified under the Brillouin gain spectrum are approaching the unity. Here, we note that our 4-µm core diameter tellurite fiber is not strictly single-mode around 2 µm and that it has linear losses of about 0.5 $dB.m^{-1}$, a low anomalous dispersion regime, and a high nonlinear Kerr coefficient about 0.12 $W^{-1}.m^{-1}$ (for details, See Ref. [17]). With the tellurite fiber, the total cavity losses were measured to be around 9.5 dB due to 2.5 dB butt-coupling loss at each fiber facet and 3.5 dB loss related to other fiber components. Regarding the heavily GeO_2-doped-core fiber with a 2-µm core diameter, it exhibits single-mode behavior at 2 µm and anomalous group-velocity dispersion, the linear losses are 0.1 $dB.m^{-1}$, its nonlinear coefficient is found to be about 0.03 $W^{-1}.m^{-1}$ (more details can be found in Ref. [18]). The GeO_2-doped-core fiber was directly spliced to other standard fiber components of the cavity (with splice loss per facet about 1 dB), so that the total cavity losses were measured to be around 5.7 dB.

3. RESULTS WITH TELLURITE FIBER

The Brillouin frequency shift (BFS, ν_B) and its linewidth were experimentally measured at 2-µm in the spontaneous regime (almost 17 dB below the Brillouin critical threshold) by using a standard heterodyne detection technique, as that described in Ref. [19].

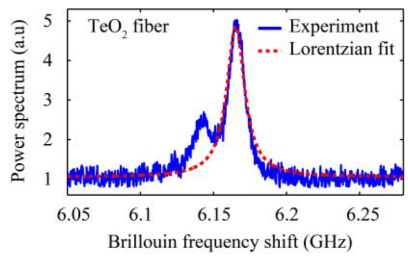

Fig. 2. Experimental Brillouin spectrum of the step-index tellurite-glass optical fiber.

Figure 2 shows~~s ν_Bs~~ the experimental Brillouin spectrum of the TeO_2-based fiber for an input power of 15 dBm. The SBS gain spectrum exhibits a main frequency peak at 6.165 GHz (BFS,) and a secondary weak peak down to 6.15 GHz. By fitting the Brillouin gain spectrum with a Lorentzian function (red dashed curve), we can estimate the Brillouin linewidth ($\Delta\nu_B$) as to 14.9 MHz, which is lower than that measured at 1.55 µm (about 21 MHz) for $\nu_B = 7.972$ GHz, the latter values at 1.55 µm are close to those previously reported in Ref [20]. Tuning the pump wavelength around 2 µm indeed slightly changes the SBS frequency and linewidth, because of the phase-matching condition that depends on the optical wavelength, as $\nu_B = 2n_{eff}V_a/\lambda_p$ where n_{eff}, V_a and λ_p are effective index, longitudinal acoustic velocity and optical wavelength, respectively. All these opto-acoustic parameters of the TeO_2-based fiber are listed in Table 1 together with other tested fibers (GeO_2, $As_{38}Se_{64}$, and SMF-28). The SBS gain coefficient can be straightforwardly estimated from the Brillouin gain linewidth using the equation in Ref. [19], and this gives $g_B = 1.05 \times 10^{-10}$ $m.W^{-1}$. The theoretical single pass Brillouin threshold (P_{th}) is 1.87 W (32.7 dBm) based on the following equation [1]:

$$P_{th} = \frac{21 \times A_{eff} \times 1.5}{g_B \times L_{eff}}, \quad (1)$$

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where A_{eff}, g_B and L_{eff} are the effective fundamental mode area, the Brillouin gain coefficient and the effective length, respectively.

Figure 3 (a) depicts the Brillouin laser spectra close to 2 µm for an increasing coupled power into the tellurite fiber from 56.2 mW to 223 mW (from 17.5 dBm to 23.5 dBm). Note that the pump power is measured from the port 1 of the OC. We clearly see that Brillouin lasing occurs from 89.1 mW (green spectrum) as an upper wavelength shift of 82 pm that matches the SBS frequency, thus confirming that the Brillouin gain is strong enough to compensate for the ring cavity losses beyond the threshold. For higher input powers, the first Stokes wave grows significantly and then generates a second-order Stokes wave and so on. We still note the presence of the backward pump at 1995 nm due to strong Fresnel reflections (about 10%) at the tellurite fiber end facet. In Fig. 3 (b), we show the Stokes power as a function of the ~~coupled~~ input pump power. The stable power effect comes from the both Fresnel reflections and Rayleigh scattering. The TeO_2-based BFL exhibits a low threshold of 98 mW for this single-pass pumping configuration. Similar experiments using 1.5 m of chalcogenide fiber ($As_{38}Se_{62}$) and 140 m of standard silica fiber (SMF-28) have been reported in Refs [14,15]. A close lasing power threshold was obtained with the chalcogenide fiber, whereas for the SMF-28 fiber it is almost five times larger due to the strong absorption at 2 µm.

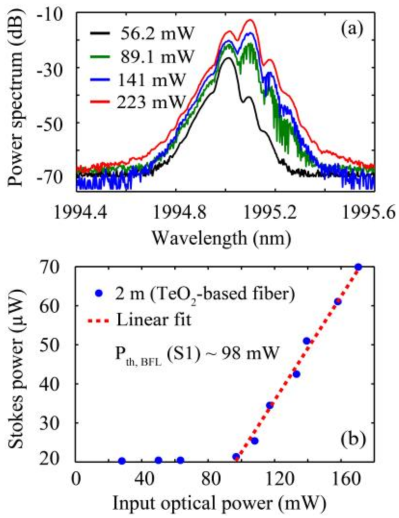

Fig. 3. (a): Experimental BFL optical spectra obtained with the TeO_2-based fiber by varying input pump power, (b): Stokes wave power versus input optical power (Port 1).

We further investigated the coherence properties of our BFLs in the electrical domain using the heterodyne detection. Figure 4 shows the recorded RF beat signal between the Brillouin laser and the reflected optical pump light. The spectrum is centered at the BFS (6.156 GHz) and the full width at half-maximum (FWHM) of the BFL is estimated to be 48 kHz using a Lorentzian fit, thus showing a significant linewidth narrowing ~~in~~ compared to the spontaneous regime (14.9 MHz, Fig. 2). We must ~~must~~ stress however that this is just a measurement of the beat signal, which is slightly greater than the laser linewidth. The delayed self-heterodyne technique [21] would be preferable to precisely measure the BFL linewidth. However, we note that this technique is difficult to implement at 2 µm due to the higher linear losses propagation in long delay silica fibers at 2 µm (around 22.2 dB/km), as described in ~~Ref~~ Ref. [14,16].

However, the BFL linewidth can be estimated based on the input laser linewidth (~~-~~100 kHz) and the ring cavity parameters by using the following equations [22]:

$$\Delta\nu_{BFL} = \frac{\Delta\nu_{pump}}{K^2}, \quad (2)$$

$$K = 1 + \frac{\pi \times \Delta\nu_B}{\frac{c}{nL} \times \ln R}, \quad (3)$$

here $\Delta\nu_{BFL}$ and $\Delta\nu_{pump}$ are the linewidths of the Stokes wave and the optical pump, respectively, and c is the speed of the light. The K factor is here estimated to be 1.51. The Brillouin fiber laser linewidth could be calculated to be 41 kHz, which is closed to the experimental value.

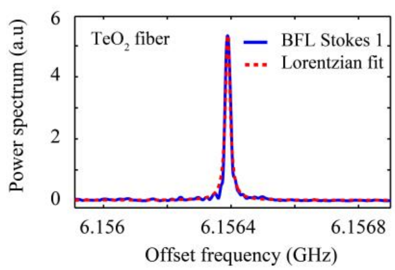

Fig. 4. Laser RF spectrum of the TeO_2-based optical fiber measured for an injected optical power of 112 mW (Port 1). RBW = 5 kHz: Resolution bandwidth of the electrical spectrum analyzer (ESA).

4. RESULTS WITH HEAVILY GERMANIA-DOPED FIBER

Both frequency and linewidth of the Brillouin gain spectrum at 2-µm (in the spontaneous regime, i.e., well below the Brillouin threshold) are again experimentally measured using the heterodyne detection in the case of a heavily GeO_2-doped-core optical fiber. In such optical fibers, it has recently been demonstrated that the Brillouin gain (dB) ~~significantly~~greatly increases with the doping level ~~by means of the pump probe technique~~ [18]. Figures 5 shows the experimental backscattering Brillouin spectrum of this fiber when injected optical power is fixed to 25 dBm (Port 2). The SBS gain spectrum exhibits a single-frequency peak centered around 6 GHz (BFS, ν_B). As expected, this value is lower than the BFS at 1.55 µm pump wavelength, found to be 7.7 GHz in Ref. [18]. The Brillouin gain spectrum is fitted with a Lorentzian spectral profile (red dashed curve), and we obtain a Brillouin linewidth ($\Delta\nu_B$) of 76 MHz, which is almost 5 times larger than that of the TeO_2-based fiber. The Germania doping here strongly contributes to the acoustic properties of the optical fiber, particularly broadening the SBS linewidth when compared to standard silica fibers ~~(see also Table 1)~~[18] (see also Table 1). The SBS gain efficiency is then estimated to be 2.04 $m^{-1}.W^{-1}$, which is almost 10 times larger than standard silica fibers (0.28 $m^{-1}.W^{-1}$). The theoretical Brillouin threshold (P_{th}) of the ~~FUT~~ fiber without cavity feedback can be calculated to be 8,764 mW (39.4 dBm). The SBS threshold is here very high due to the short length (1.8 m) used in our experiment. ~~In such optical fibers, it has recently been demonstrated that the Brillouin gain (dB) significantly increases with the doping level by means of the pump probe technique [18].~~

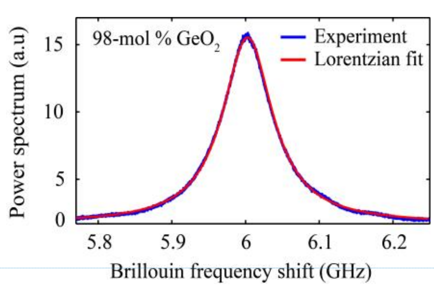

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Fig. 5. Experimental Brillouin spectrum of the 98-mol % GeO_2-doped-core fiber obtained for an injected optical power of 25 dBm (Port 2).

Figure 6 (a) shows the recorded optical Brillouin laser spectra at 2 µm using the GeO_2-doped fiber based cavity, when coupled optical power is increased from 27 dBm to 29.5 dBm (501 mW to 891 mW). We note that the Brillouin lasing effect occurs around 28.5 dBm (orange spectrum). Beyond the laser threshold, we again retrieve a cascade of Stokes waves.

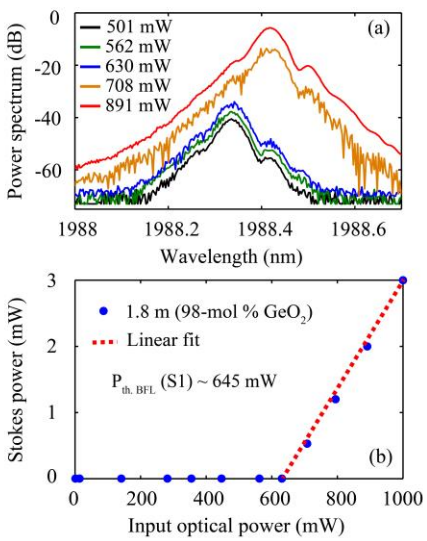

Fig. 6. (a): Experimental Brillouin laser spectra of the heavily GeO_2-doped-core optical fiber with an increased input pump power, (b): Extracted Stokes wave power versus injected optical power (Port 1).

The reflected laser pump can be observed on the short wavelength side centered at 1988.35 nm due to the Fresnel reflection estimated to be around 5 %. In Fig. 6 (b), we show the Stokes wave power as a function of the coupled input pump power (Port 1). The GeO_2-doped-core fiber exhibits a lasing threshold of 645 mW for this single-pass pumping configuration, which is very high compared to the TeO_2-based fiber. Figure 7 depicts the RF beat signal between the Brillouin laser and the reflected optical pump light when the coupled input power is 707 mW (Port 1). The resulting RF spectrum is centered at the Brillouin frequency of 6 GHz and the FWHM of the BFL laser is estimated to be 1.5 MHz, which is very large compared to the expected value (7.4 kHz) calculated with Eqs. (2) and (3).

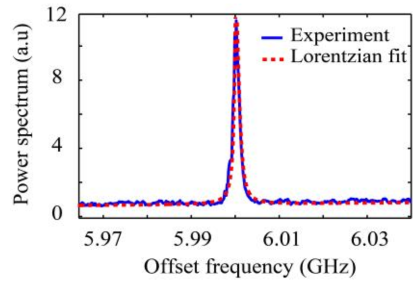

Fig. 7. Output Brillouin laser RF spectrum of the heavily GeO_2-doped-core optical fiber (98-mol %) at 707 mW as injected optical power.

5. DISCUSSION AND CONCLUSION

Table 1 summarizes all the experimental and theoretical results of this paper and shows the comparison of both optical and acoustic properties between optical fiber samples used in this work and recent other studies at 2-µm wavelength. Both effective index (n_{eff}) of the fundamental optical mode and effective area (A_{eff}) were numerically calculated using a finite element method (COMSOL software) and including opto-geometric parameters of the FUTfibers. From Table 1, we can underline the strong Brillouin gain efficiency of the tellurite fiber in the 2µm band, about 52 times larger than SMF-28, as well as the low laser threshold. It is worth noting that the SBS gain efficiency of the $As_{38}Se_{64}$ optical fiber remains very high compared to all fiber materials presented in the table. For all fibers, BFL linewidths measurements are listed, but the delayed self-heterodyne technique cannot be used due to the high linear losses at 2-µm when km-long delay fibers are required. Another technique would be preferable in this wavelength region.

Table 1. Optoacoustic and Brillouin lasing parameters of tellurite (TeO_2), Germanium (GeO_2), chalcogenide ($As_{38}Se_{64}$) and standard silica optical fibers (SMF-28).

Optical fiber	TeO_2*	GeO_2*	$As_{38}Se_{64}$**	SMF-28***
Core size, Φ (µm)	4	2	4.5	8.2
Loss, α (dB.m^{-1})	0.5	0.1	2.2	0.022
Length, L (m)	2	1.8	1.5	14
Eff. Length, L_{eff} (m)	1.6	1.76	1.13	13.5
Eff. Area, A_{eff} (µm^2)	10	5	8	101
Ref. index, n	1.968	1.580	2.81	1.45
Eff. Index, n_{eff}	1.944	1.514	-	1.443
Acoustic Velocity, V_a (m.s^{-1})	3155	3898	2173	5960
Mass Density, ρ (kg.m^{-3})	6000	3596	-	2210
SBS frequency, ν_B (GHz)	6.165	6.00	6.258	8.38
SBS Linewidth, $\Delta\nu_B$ (MHz)	14.9	76	21.5	15
SBS gain coef. g_B ($\times 10^{-11}$ m.W^{-1})	10.5	1.02	350	2.87

SBS efficiency, g_B/A_{eff} ($m^{-1}.W^{-1}$)	10.5	2.04	437.5	0.28
SBS Threshold, P_{th} (W)	1.871	8.764	0.0914	8.203
BFL Threshold, $P_{th,S1}$ (mW)	98	645	52	1040
BFL Linewidth, $\Delta\nu_{BFL}$ (kHz)	48	1500	4000	8

* Values from this work
** Values from Ref. [15]
*** Values from Ref. [14,23]

To conclude, a close-to-single frequency Brillouin fiber laser has been demonstrated at 2-µm wavelength using a short length (≤2 m) of either step-index tellurite fiber or heavily GeO_2-doped-core silica fiber. The backscattering SBS characterization reported shows a strong enhancement of the Brillouin gain efficiency compared to standard silica fibers at 2-µm. A BFL threshold of 98 mW and 645 mW have been obtained in the passive ring cavity, respectively, while the BFL linewidth is found to be 48 kHz and 1.5 MHz. Improvement of the cavity losses is under study in the particular case of tellurite fiber to advantageously increase the laser efficiency. This simple configuration of BFL laser is proposed as a promising candidate for developing narrow-linewidth laser sources in the 2 µm band and beyond for molecular gases sensing, spectroscopy and bio-photonics applications towards the mid-infrared.

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